Copy 376
RM L56E14

CONFIDENTIAL

NACA RM L56E14

RESEARCH MEMORANDUM

INVESTIGATION OF UNSTEADY FLOW PAST FOUR NACA 6-PERCENT-THICK AIRFOIL SECTIONS

By Charles L. Ladson and Walter F. Lindsey

Langley Aeronautical Laboratory
Langley Field, Va.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

July 26, 1956

CONFIDENTIAL

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

INVESTIGATION OF UNSTEADY FLOW PAST FOUR NACA 6-PERCENT-THICK AIRFOIL SECTIONS

By Charles L. Ladson and Walter F. Lindsey

SUMMARY

An investigation of the intensity of root-mean-square pressure pulsations and root-mean-square normal-force-coefficient fluctuations has been conducted on two NACA high-lift airfoils and two NACA 6-series airfoils. The results at Mach numbers and normal-force coefficients where the fluctuations and pulsations attained significant magnitudes indicated that the NACA high-lift airfoil sections were inferior to the NACA 6-series airfoils with respect to both pulsating pressures and fluctuating forces. It was also observed that an airfoil section which has low values of fluctuating normal force may, because of phase effects, have higher values of pulsating pressures or local panel loads than an airfoil section which has a higher value of fluctuating normal force.

INTRODUCTION

Several symmetrical 6-percent-thick airfoil sections were designed to have high maximum-lift coefficients at low speeds. (See refs. 1 and 2.) The aerodynamic characteristics of these profiles indicated that two of the new airfoil sections (NACA 2-006 and 4-006) had low-speed maximum-lift coefficients of about 1.2 at a Reynolds number of 9×10^6, as compared with values of about 0.8 for other 6-percent-thick symmetrical airfoil sections. No significant differences in the lift and moment characteristics of these new high-lift airfoils as compared with the NACA 64-006 airfoil section were found at high subsonic Mach numbers. (See refs. 1 and 2.)

Pressure pulsations on airfoils of this general type were restricted to data obtained from tests on an NACA 2-008 airfoil at the Ames Aeronautical Laboratory. (See ref. 3.) These results indicated that at the higher Mach numbers the airfoils had very unsteady flow characteristics. This NACA 2-008 airfoil, however, was linearly scaled from an NACA 2-006 and the method of derivation does not permit linear scaling

[redacted]

of the thickness form. Also, former investigations in the Langley 4- by 19-inch semiopen tunnel indicated that the unsteady flow about airfoils was considerably reduced at high subsonic Mach numbers by using thinner airfoil sections. (See ref. 4.)

It was therefore desirable to conduct an unsteady-flow investigation at transonic Mach numbers on NACA 2-006 and 4-006 airfoil sections designed to have high maximum-lift coefficients at low speeds and compare their performances with the performances of NACA 64A006 and 65A006 airfoils. The tests covered a Mach number range from 0.6 to 1.0, an angle-of-attack range from 0° to 8°, and a Reynolds number range of 1.6×10^{6} to 2.1×10^{6}. A concurrent investigation on the NACA 2-006 airfoil was conducted at the Ames Aeronautical Laboratory. (See ref. 5.)

SYMBOLS

M	free-stream Mach number
T	an arbitrary period of time
c	chord of model
p_{av}	time-average value of p_i
p_i	instantaneous local static pressure on airfoil surface
q	free-stream dynamic pressure
t	time
x	distance along chord
α	angle of attack
$\overline{\Delta P}$	root-mean-square pressure-pulsation coefficient, $\frac{1}{q}\sqrt{\frac{1}{T}\int_0^T \left(p_i - p_{av}\right)^2 dt}$
$\overline{\Delta P_{av}}$	chordwise average of $\overline{\Delta P}$, $\frac{1}{c}\int_0^c \overline{\Delta P}\, dx$

c_n section normal-force coefficient

$\overline{\Delta c_n}$ root-mean-square normal-force-coefficient fluctuation

APPARATUS, MODELS, AND TESTS

The tests were conducted in the Langley 4- by 19-inch semiopen tunnel. (See fig. 1.) Dried air from the settling chamber at a stagnation pressure of 20 lb/sq in. abs flowed through the test section and was discharged through the diffuser into the atmosphere. Test-section Mach numbers were regulated by a variable-area throat located downstream of the test section. The tunnel calibration and operation were similar to that described in reference 6.

Jet-boundary corrections for neither this type of test nor steady-state tests have yet been determined at high subsonic Mach numbers; therefore, no correction has been applied to any of these data. The major correction to which the steady-state data are subject is the correction to angle of attack and is given for low speeds (for the tunnel configuration used) by $\alpha_{true} = \alpha_{test} - 1.85c_n$ (derived from ref. 7).

The 4-inch-chord models investigated and their locations of maximum thickness are as follows:

Airfoil	Position of maximum thickness, percent chord
NACA 2-006	14.5
NACA 4-006	25.5
NACA 64A006	39.0
NACA 65A006	42.5

The ordinates for the NACA 2-006 and 4-006 airfoil sections are given in references 1 and 2 and those for the NACA 65A006 and 64A006 airfoil sections are given in references 4 and 8, respectively. Pressure orifices were located on the upper surfaces of the models at the 3.1-, 14-, 25-, 37.5-, 50-, 62.5-, 75-, and 87.5-percent-chord stations. No orifices were located on the lower surface inasmuch as previous studies had shown that the principal contribution to the unsteady pressures is made by the upper surface at moderate and high angles of attack. (See ref. 4.)

Miniature electrical differential-pressure gages were connected with very short tubes to each of the eight orifices at one end of the model (25-percent spanwise station) and connected by long, small-diameter tubes to similarly located orifices at the other end of the model (75-percent spanwise station). The long tubing damped out all pulsations to provide the time-average pressure. The output of the gages was then proportional to the difference between the instantaneous local pressure p_i and the time-average or "steady-state" pressure p_{av}.

The electrical outputs from each gage were fed into electronic equipment which included vacuum thermocouples (American Thermo Electric Company, type 17A). By means of this equipment the mean square of the pulsating pressure for each orifice $\left(\frac{1}{T}\int_0^T \left(p_i - p_{av}\right)^2 dt\right)$ and the mean square of the normal-force fluctuation were simultaneously recorded on oscillograph records. A sample of an oscillograph record, presented in figure 2, shows that little variation occurred in the recorded values during the approximate 5-second record duration. This information was easily transposed into root-mean-square pressure-pulsation coefficient $\overline{\Delta P}$ and root-mean-square normal-force-coefficient fluctuations $\overline{\Delta c_n}$. The values presented herein are the total measured quantities from which no deductions for tunnel-empty level were made. One high-lift and one 6-series airfoil were retested at an angle of attack of 4°. Data from both the original tests and the repeat tests are presented and compared in figure 3 to provide an indication of the accuracy of the measurements. The repeatability is considered very good.

Root-mean-square pressure-pulsation and root-mean-square normal-force-coefficient-fluctuation data were obtained for the four airfoils at angles of attack from 0° to 8°. The Mach number ranged from 0.6 to 1.0 and the corresponding Reynolds numbers were approximately 1.6×10^6 to 2.1×10^6.

RESULTS AND DISCUSSION

Factors Affecting Comparison of Data From Various Test Facilities

The root-mean-square normal-force-coefficient-fluctuation data in this report may be compared with previous data from the same facility on 9-percent-thick airfoils (ref. 9), but the root-mean-square pressure-pulsation data presented herein are not numerically comparable with the double-amplitude pressure-pulsation results of references 4, 8, and 9.

Comparisons of data from various facilities are subject to many differences. For the steady-state aerodynamic characteristics, a careful comparison of a multitude of available data from various sources has shown differences to exist in numerical values. However, the trends due to changes in airfoil-shape factors are in general agreement. Differences in the numerical values were attributable to differences in Reynolds number, model surface conditions, tunnel turbulence, and, more significantly, jet-boundary effects.

Data from unsteady flow investigations would be affected not only by the aforementioned factors but also by wide differences which do exist in the testing techniques and in the transcription and reduction of data. Data trends due to profile changes and other variables should be established even though the numerical values are not comparable.

In some cases, conclusions from different unsteady flow investigations can be in disagreement; for example, the beneficial effects of camber at moderate Mach numbers and high-lift coefficients were established by reference 8. Reference 5, however, concluded that camber is ineffective but neglected to restrict that conclusion to values of lift coefficient below 0.6. At higher lift coefficients the data of reference 5 substantiate those of reference 8. Similar results are observed in the effects of maximum-thickness location as presented by references 4 and 5, and on thickness effects (refs. 3, 4, and 5).

Root-Mean-Square Pressure Pulsations

The chordwise variations of pulsating pressures are indicative of local panel loads. These data are presented in figure 4 to show the change in unsteady load distributions with Mach number for several constant values of normal-force coefficient for each of the four airfoils.

At low normal-force coefficients (0.2 and below) the pressure-pulsation level was low and no one airfoil can be chosen as having the lowest values throughout the Mach number range. However, for normal-force coefficients of 0.6 and 0.675, the NACA 2- and 4-series high-lift airfoils show significantly higher values of $\overline{\Delta P}$ than do the NACA 6-series airfoils.

Of the NACA 6-series airfoils, the NACA 64A006 airfoil not only encounters higher pressure pulsations near the leading edge at Mach numbers of 0.6 and 0.7 and normal-force coefficients of 0.4 and higher, but also has constantly higher values of root-mean-square pressure pulsations along the chord than the NACA 65A006. This result is in agreement with the conclusion of reference 8, although the magnitude of the differences in the present investigation is not as great as previously indicated.

Differences in relative magnitudes between the two investigations may be partially attributable to refinements in instrumentation and to a Reynolds number that was 25 percent higher for the present investigation.

Root-Mean-Square Force Fluctuations

The variations in the root-mean-square normal-force fluctuation $\overline{\Delta c_n}$ with Mach number for the four 6-percent-thick airfoils at several constant values of normal-force coefficient are shown in figure 5.

For values of normal-force coefficient of 0.2 and 0.4, the force fluctuations throughout the Mach number range are small and so nearly equal for the four airfoils that no one can be selected as best. At normal-force coefficients of 0.6 and 0.675, the NACA 64A006 and 65A006 airfoils have lower values of force fluctuations than the NACA 2-006 and 4-006 up to a Mach number of about 0.9. For Mach numbers from 0.9 to 1.0 the airfoils have low values of $\overline{\Delta c_n}$ and the relatively small incremental differences are considered insignificant. These results are in general agreement with the results of reference 9 on 9-percent-thick airfoils. Reference 9 indicated that shape had little effect on $\overline{\Delta c_n}$ for values of lift coefficient up to about 0.6. At higher values of lift coefficient, however, airfoils from reference 9 with the more rearward position of maximum thickness had lower levels of $\overline{\Delta c_n}$. However, the changes in section from 64A006 to 65A006 did not produce the reduction in force fluctuations on the 6-percent-thick airfoils of this investigation as was observed on the 9-percent-thick airfoils (ref. 9). A reduction in effect of shape may be attributed to the fact that as the maximum thickness on airfoils is reduced, the shape becomes less significant.

Phase effects.- The pulsating pressures $\overline{\Delta P}$ at various chordwise stations differ in their time histories because of the finite velocity of propagation of pressure disturbances, and thus produce phase effects in the comparisons of pressure pulsations with normal-force fluctuations. (See ref. 4.)

Figure 5 indicates that the NACA 64A006 airfoil has somewhat lower values of $\overline{\Delta c_n}$ than the NACA 65A006. The NACA 65A006 airfoil, however, had the lowest values of pulsating pressure or panel loads. (See fig. 4.)

Since fluctuating panel loads $\overline{\Delta P}$ and fluctuating normal forces $\overline{\Delta c_n}$ were measured simultaneously, these data indicate that large differences exist in the effects of phase on the two airfoils. This result, although not observed in the data for the two high-lift airfoils, does indicate that large panel loads might occur without being accompanied by large fluctuating normal forces.

Additional information on phase effects is shown in figure 6, which presents a comparison of the chordwise average of the pulsating pressures $\overline{\Delta P_{av}}$ with the normal-force-coefficient fluctuation $\overline{\Delta c_n}$ for the NACA 65A006 airfoil. The general convergence of the curves in figure 6 and a reduction in the effects of unsteady flow as the Mach number approaches 1.0 is a direct result of the motion of the shock or separation point or both the shock and the separation point rearward along the airfoil surface and toward the trailing edge of the model, as indicated by figure 4. The magnification of differences between $\overline{\Delta P_{av}}$ and $\overline{\Delta c_n}$ with increase in angle of attack is produced by an increase in phase effects and is a result of the growth of shock strength and increased extent of separation, as again indicated in figure 4. (See also ref. 4.) The comparison in figure 6 shows that the value of $\overline{\Delta P_{av}}$ is approximately twice that for $\overline{\Delta c_n}$ at angles of attack of 0° and 4°, while at 8° it averages about three times the value. These differences are attributed to the chordwise phase variations in the pulsating pressure. The pulsating pressures were noted in reference 9 to be nearly in phase at low angles of attack and were as much as 180° out of phase at angles of attack above 6°. The ratios of $\overline{\Delta P_{av}}$ to $\overline{\Delta c_n}$ are lower in the present investigation of 6-percent-thick airfoils (ref. 9) since $\overline{\Delta P_{av}}$ is based on root-mean-square values. However, the change in ratio with angle of attack is generally proportional to that observed in reference 9.

Effect of airfoil thickness.- In order to extend information on the effects of thickness, the 6-percent-thick airfoils of the NACA 64A- and 65A-series from the present investigation are compared with 9-percent-thick airfoils of the same series from reference 8. Figures 7(a) and (b) compare the root-mean-square normal-force fluctuations from these two investigations. For Mach numbers below 0.8 and values of c_n below 0.4, the fluctuating forces are about the same for the two thicknesses. However, for values of c_n above 0.4 and Mach numbers below 0.8, the 6-percent-thick airfoils show rapid increase in fluctuating force at lower values of c_n than do the 9-percent-thick airfoils. This is due to the fact that the attitude or angle of attack for leading-edge flow separation on 6-percent-thick airfoils is less than that for the 9-percent-thick airfoils. (See refs. 4 and 6.) At Mach numbers from 0.9 to 1.0, the 6-percent-thick airfoils exhibit much lower levels of fluctuating force than the 9-percent-thick airfoils up to a normal-force coefficient of approximately 0.7 and thus confirm earlier investigations (refs. 3 and 9) in that thicker airfoils are inferior in the high subsonic speed range.

CONCLUSIONS

A two-dimensional wind-tunnel investigation of the intensities of root-mean-square pressure pulsations and root-mean-square normal-force fluctuations on two NACA high-lift airfoil sections and two NACA 6-series airfoils indicated that

1. At low normal-force coefficients, the levels of both root-mean-square fluctuating forces and pressures were low and about equal for the four airfoil sections. For normal-force coefficients of 0.6 and above, the conventional NACA 6-series airfoil sections had considerably lower values of pulsating pressures or panel loads. The maximum values of fluctuating normal-force coefficients were encountered on the high-lift airfoils.

2. Because of phase effects, it may be possible for an airfoil section which has a low value of fluctuating force to have higher local panel loads than an airfoil section which has a higher value of fluctuating forces.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 27, 1956.

REFERENCES

1. Loftin, Laurence K., Jr., and von Doenhoff, Albert E.: Exploratory Investigation at High and Low Subsonic Mach Numbers of Two Experimental 6-Percent-Thick Airfoil Sections Designed To Have High Maximum Lift Coefficients. NACA RM L51F06, 1951.

2. Paradiso, Nicholas J.: Investigation at High and Low Subsonic Mach Numbers of Two Symmetrical 6-Percent-Thick Airfoil Sections Designed To Have High Maximum Lift Coefficients at Low Speeds. NACA RM L52I02, 1952.

3. Coe, Charles F., and Mellenthin, Jack A.: Buffeting Forces on Two-Dimensional Airfoils As Affected by Thickness and Thickness Distribution. NACA RM A53K24, 1954.

4. Humphreys, Milton D.: Pressure Pulsations on Rigid Airfoils at Transonic Speeds. NACA RM L51I12, 1951.

5. Polentz, Perry P., Page, William A., and Levy, Lionel L., Jr.: The Unsteady Normal-Force Characteristics of Selected NACA Profiles at High Subsonic Mach Numbers. NACA RM A55C02, 1955.

6. Daley, Bernard N., and Dick, Richard S.: Effect of Thickness, Camber, and Thickness Distribution on Airfoil Characteristics at Mach Numbers Up to 1.0. NACA TN 3607, 1956. (Supersedes NACA RM L52G31a.)

7. Katzoff, S., Gardner, Clifford S., Diesendruck, Leo, and Eisenstadt, Bertram J.: Linear Theory of Boundary Effects in Open Wind Tunnels With Finite Jet Lengths. NACA Rep. 976, 1950. (Supersedes NACA TN 1826.)

8. Humphreys, Milton D., and Kent, John D.: The Effects of Camber and Leading-Edge-Flap Deflection on the Pressure Pulsations on Thin Rigid Airfoils at Transonic Speeds. NACA RM L52G22, 1952.

9. Humphreys, Milton D.: Measurements of Normal-Force-Coefficient Fluctuation on Four 9-Percent-Thick Airfoils Having Different Locations of Maximum Thickness. NACA RM L54B22, 1954.

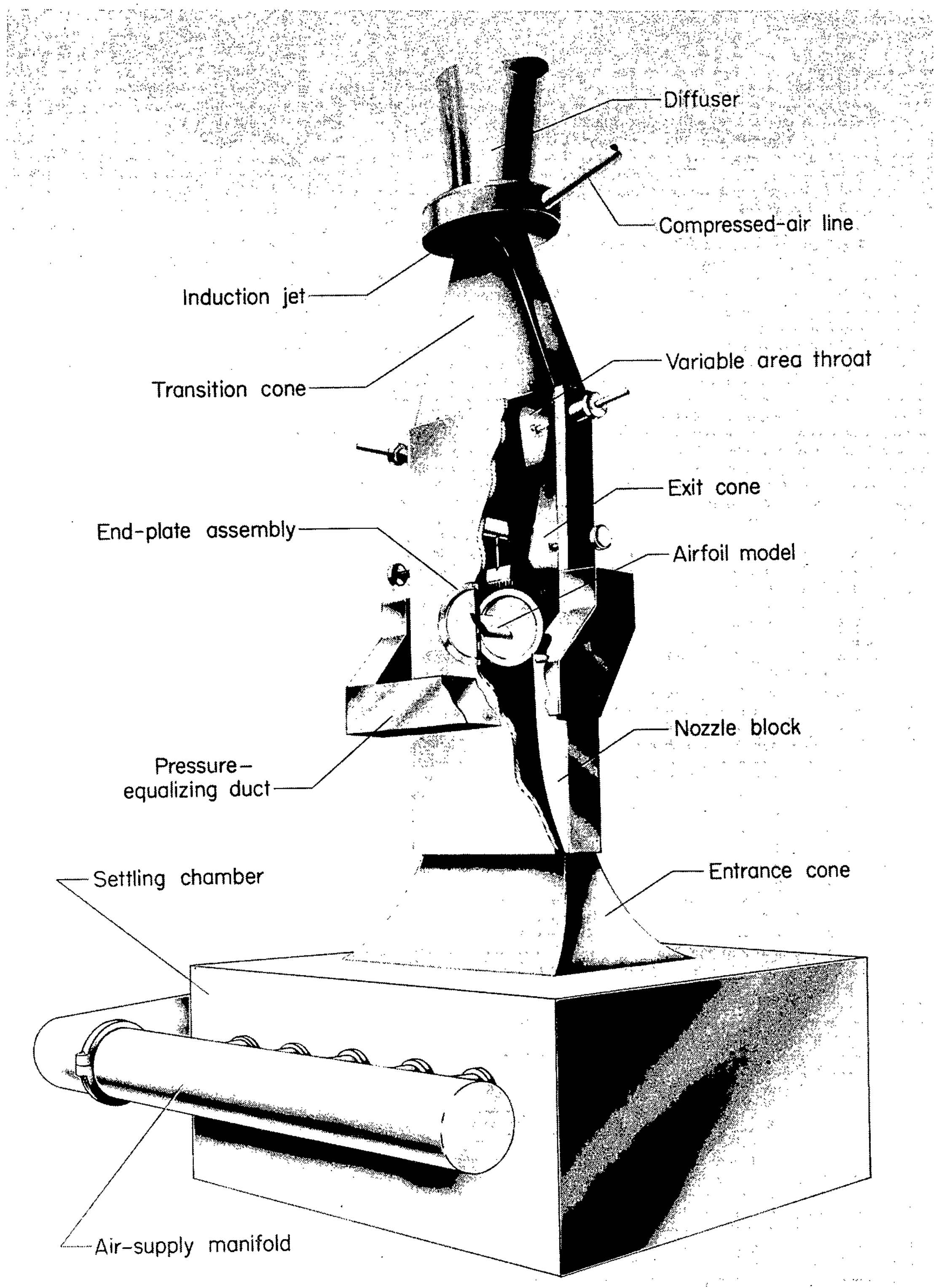


Figure 1.- Langley 4- by 19-inch semiopen tunnel. L-83293.1

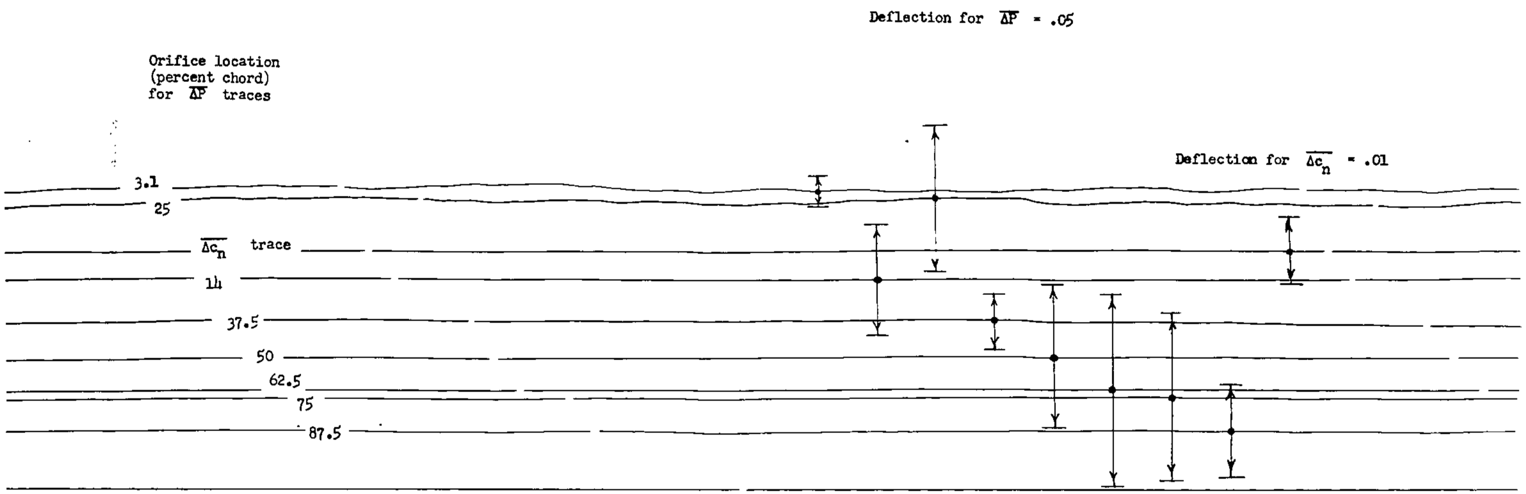


Figure 2.- Oscillograph record for NACA 65A006 airfoil section. $\alpha = 8^{\circ}$; $M = 0.70$.

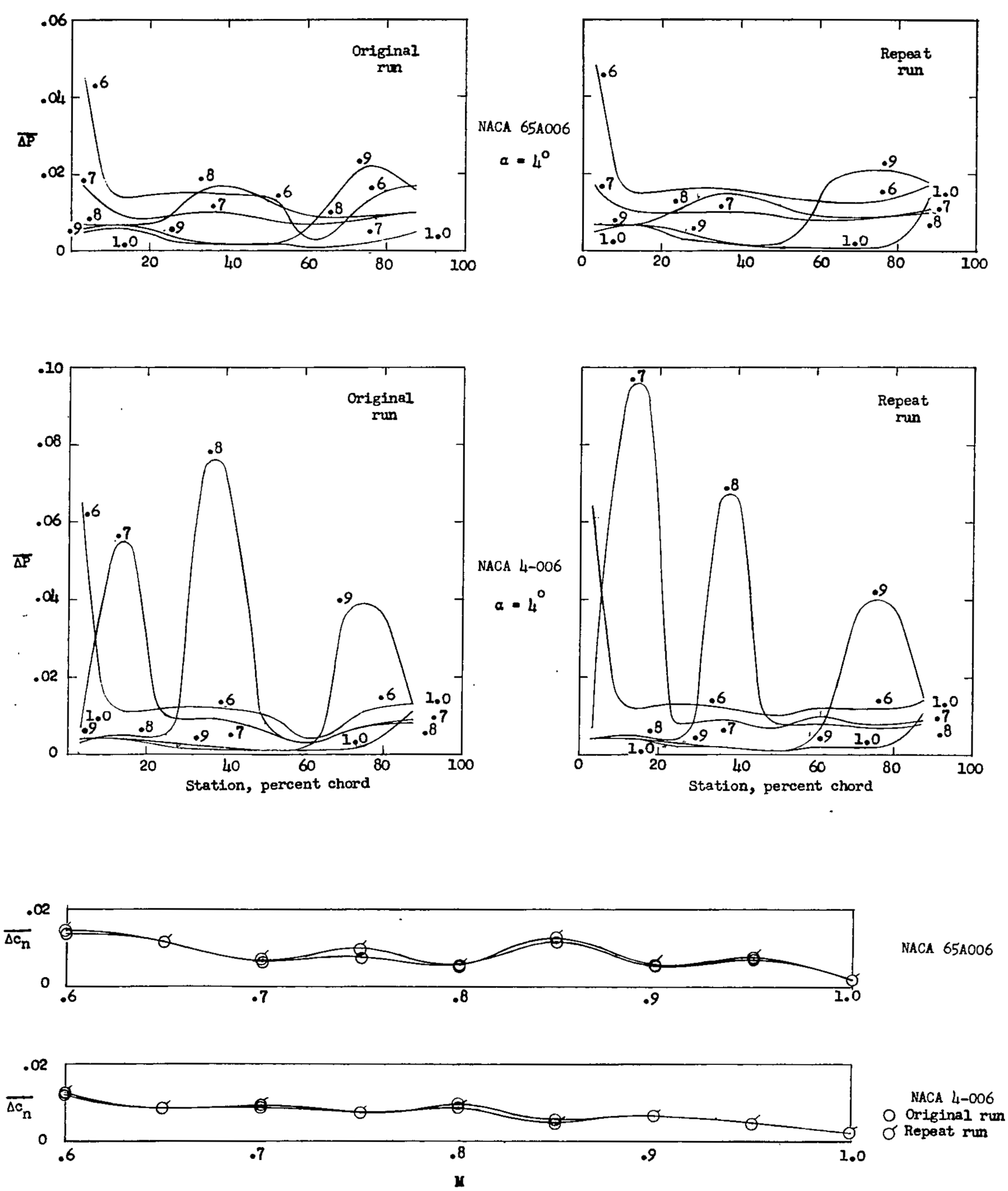
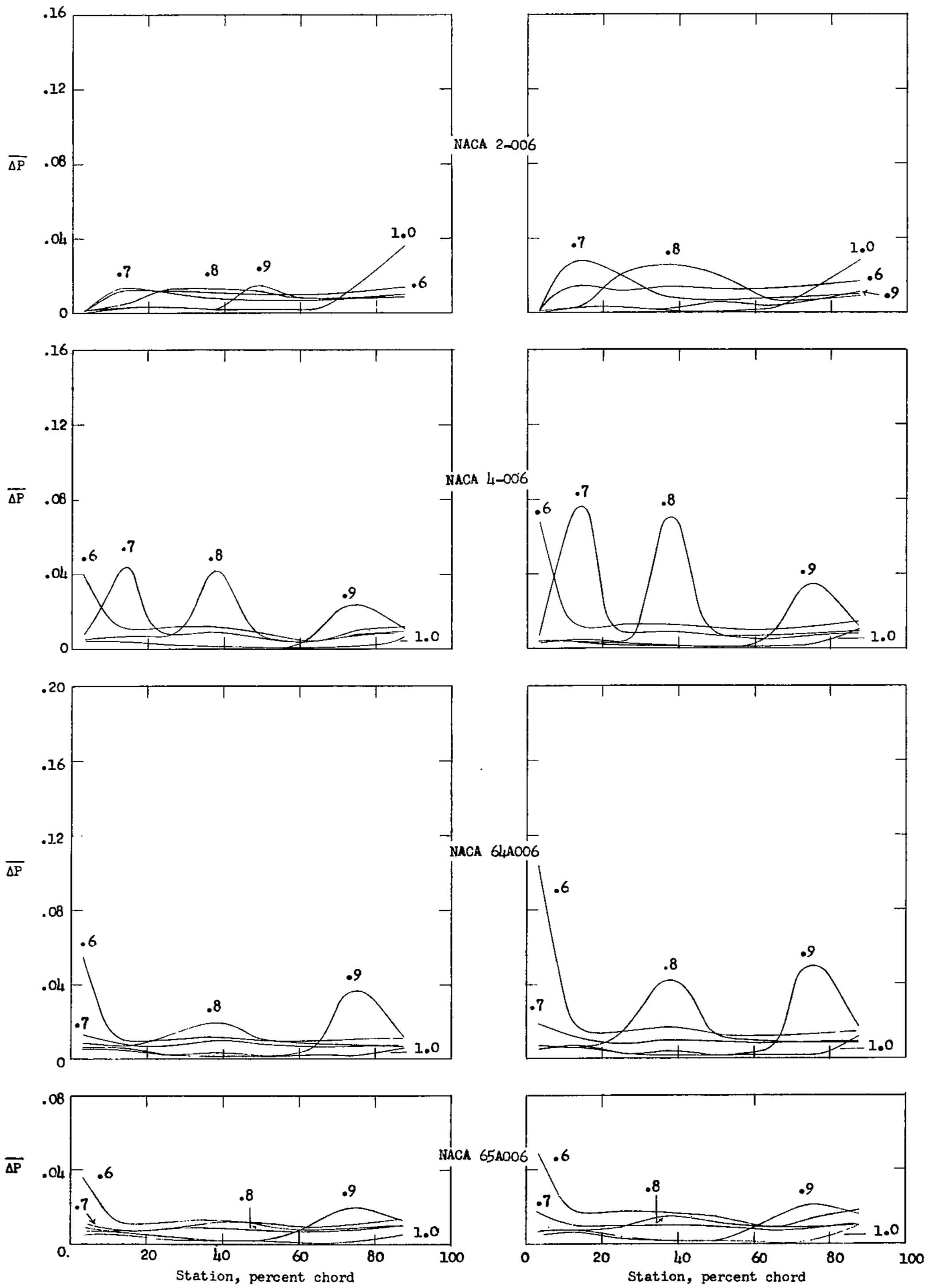


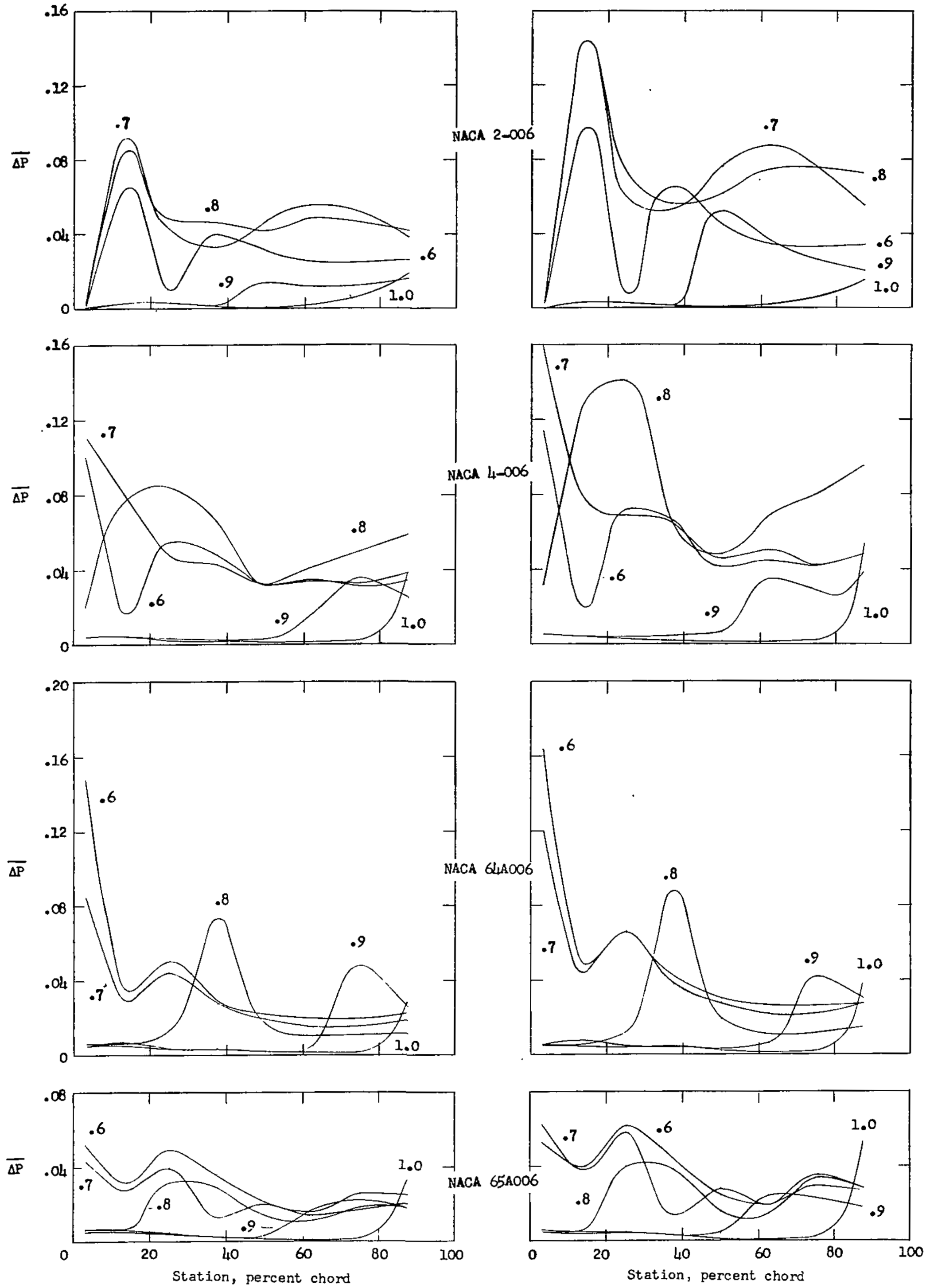
Figure 3.- Comparison of $\overline{\Delta P}$ and $\overline{\Delta c_n}$ for original run and repeat run.

[redacted]



(a) $c_n = 0.2$. (b) $c_n = 0.4$.

Figure 4.- Chordwise variation of panel loading.



(c) $c_n = 0.6$.

(d) $c_n = 0.675$.

Figure 4.- Concluded.

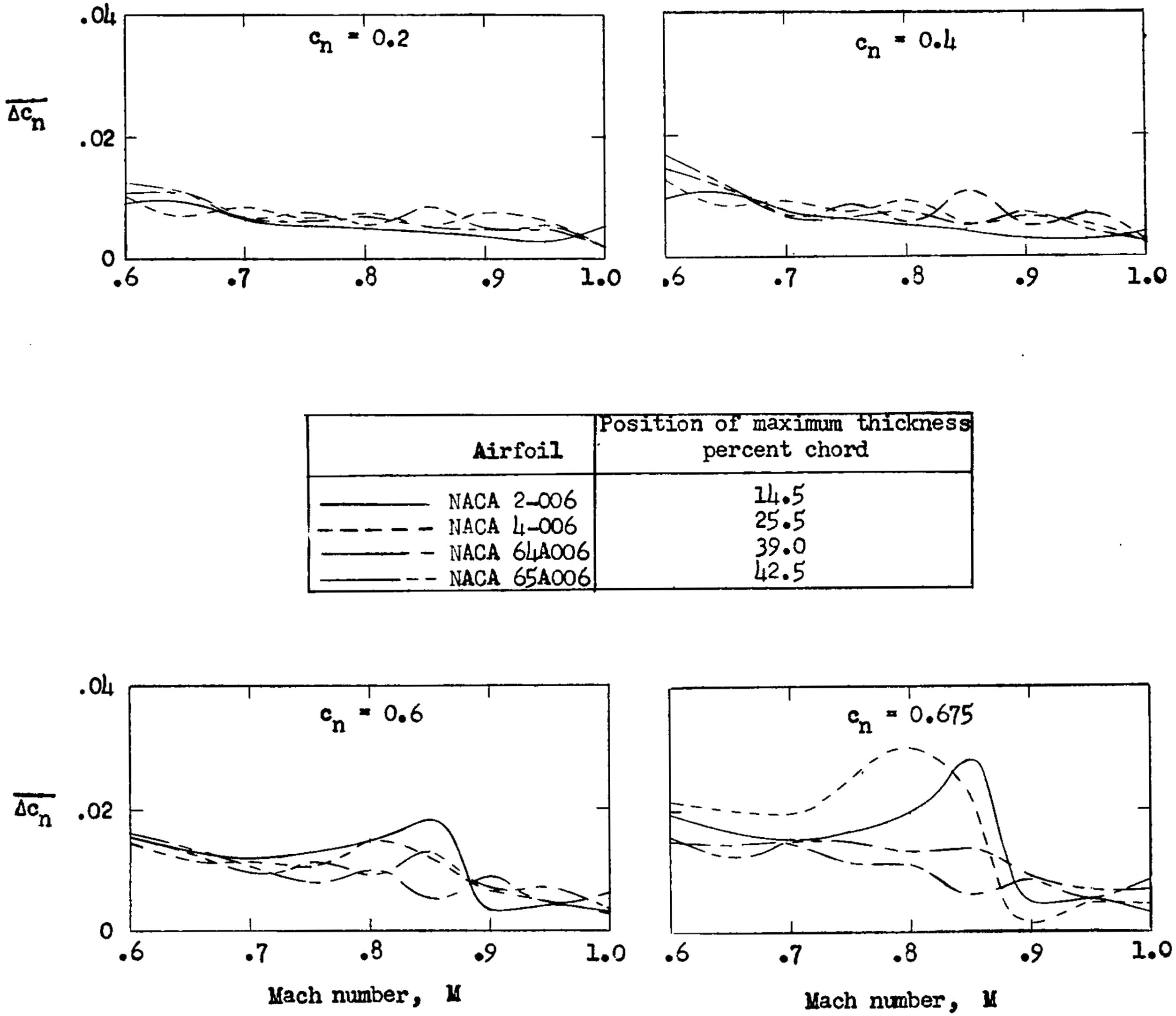


Figure 5.- Effects of section shape on fluctuating normal-force coefficient.

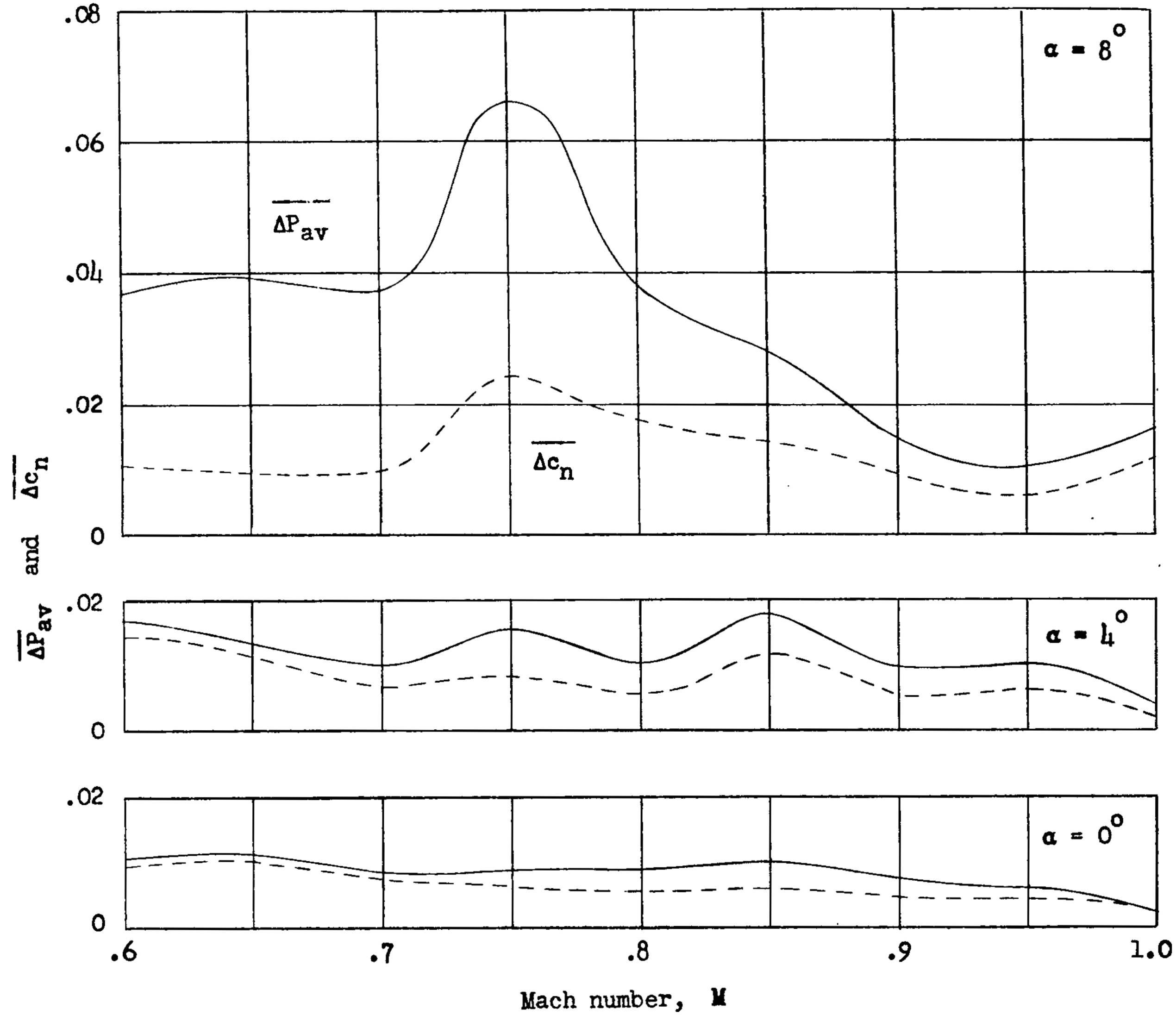
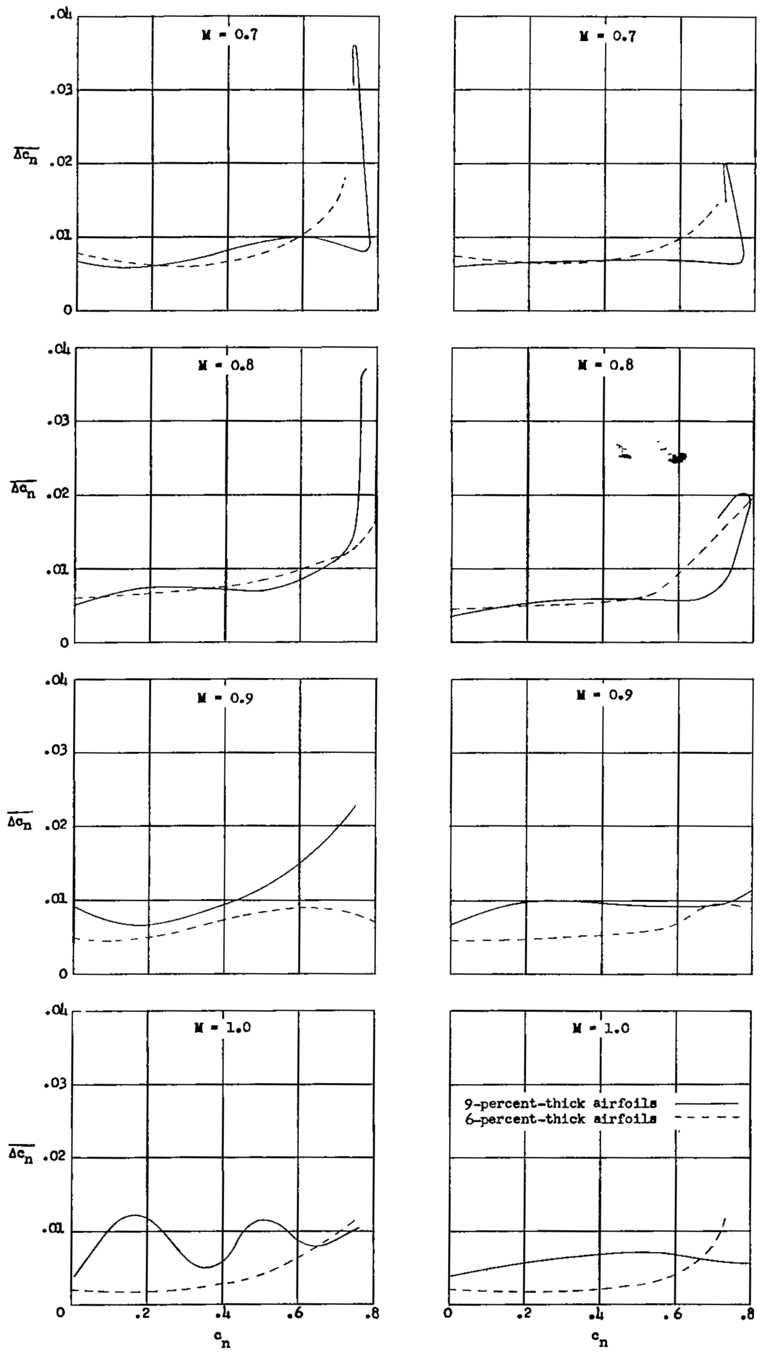


Figure 6.- Phase effects on NACA 65A006 airfoil section.



(a) NACA 64A-series. (b) NACA 65A-series.

Figure 7.- Change in fluctuating normal-force coefficient with thickness.

CONFIDENTIAL